

Contents

1	Introduction	1
1.1	Introduction to Scanning Tunneling Microscopy	4
1.2	Introduction to Atomic Force Microscopy	7
1.3	A Short History of Scanning Probe Microscopy	10
1.4	Summary	11
 Part I Scanning Probe Microscopy Instrumentation		
2	Harmonic Oscillator	15
2.1	Free Harmonic Oscillator	15
2.2	Driven Harmonic Oscillator	17
2.3	Driven Harmonic Oscillator with Damping	19
2.4	Transients of Oscillations	23
2.5	Dissipation and Quality Factor of a Damped Driven Harmonic Oscillator	25
2.6	Effective Mass of a Harmonic Oscillator	26
2.7	Linear Differential Equations	28
2.8	Summary	29
3	Technical Aspects of Scanning Probe Microscopy	31
3.1	Piezoelectric Effect	31
3.2	Extensions of Piezoelectric Actuators	34
3.3	Piezoelectric Materials	37
3.4	Tube Piezo Element	39
3.4.1	Resonance Frequencies of Piezo Tubes	43
3.5	Flexure-Guided Piezo Nanopositioning Stages	45
3.6	Non-linearities and Hysteresis Effects of Piezoelectric Actuators	46
3.6.1	Hysteresis	46
3.6.2	Creep	49

3.6.3	Thermal Drift	50
3.7	STM Tip Preparation	50
3.8	Vibration Isolation	52
3.8.1	Isolation of the Microscope from Outer Vibrations	52
3.8.2	The Microscope Considered as a Vibrating System	56
3.8.3	Combining Vibration Isolation and a Microscope with High Resonance Frequency	58
3.9	Building Vibrations	61
3.10	Summary	63
4	Scanning Probe Microscopy Designs	65
4.1	Nanoscope	65
4.2	Inertial Sliders	66
4.3	Beetle STM	71
4.4	Pan Slider	72
4.5	KoalaDrive	73
4.6	Tip Exchange	75
4.7	Summary	75
5	Electronics for Scanning Probe Microscopy	77
5.1	Voltage Divider	77
5.2	Impedance, Transfer Function, and Bode Plot	78
5.3	Output Resistance/Input Resistance	80
5.4	Noise	81
5.5	Operational Amplifiers	82
5.5.1	Voltage Follower/Impedance Converter	83
5.5.2	Voltage Amplifier	84
5.6	Current Amplifier	86
5.7	Feedback Controller	88
5.7.1	Proportional Controller	89
5.7.2	Proportional-Integral Controller	90
5.8	Feedback Controller in STM	91
5.9	Implementation of an STM Feedback Controller	94
5.10	Digital-to-Analog Converter	96
5.11	Analog-to-Digital Converter	97
5.12	High-Voltage Amplifier	98
5.13	Summary	99

6 Lock-In Technique 101
6.1 Lock-In Amplifier—Principle of Operation. 101
6.2 Summary 105

7 Data Representation and Image Processing 107
7.1 Data Representation. 107
7.2 Image Processing 112
7.3 Data Analysis 113
7.4 Summary 114

8 Artifacts in SPM. 115
8.1 Tip-Related Artifacts 115
8.2 Other Artifacts 119
8.3 Summary 121

**9 Work Function, Contact Potential, and Kelvin Probe
Scanning Force Microscopy. 123**
9.1 Work Function 123
9.2 Effect of a Surface on the Work Function 124
9.3 Surface Charges and External Electric Fields 126
9.4 Contact Potential. 129
9.5 Measurement of Work Function by the Kelvin Method 129
9.6 Kelvin Probe Scanning Force Microscopy (KFM) 131
9.7 Summary 132

10 Surface States. 135
10.1 Surface States in a One-Dimensional Crystal 135
10.2 Surface States in 3D Crystals 139
10.3 Surface States Within the Tight Binding Model 140
10.4 Summary 141

Part II Atomic Force Microscopy (AFM)

11 Forces Between Tip and Sample 145
11.1 Tip-Sample Forces 145
11.2 Snap-to-Contact 149
11.3 Summary 155

12 Technical Aspects of Atomic Force Microscopy (AFM). 157
12.1 Requirements for Force Sensors 157
12.2 Fabrication of Cantilevers. 159
12.3 Beam Deflection Atomic Force Microscopy 161

12.3.1	Sensitivity of the Beam Deflection Method	162
12.3.2	Detection Limit of the Beam Deflection Method	164
12.4	Other Detection Methods	165
12.5	Calibration of AFM Measurements	167
12.5.1	Experimental Determination of the Sensitivity Factor in AFM	167
12.5.2	Calculation of the Spring Constant from the Geometrical Data of the Cantilever	168
12.5.3	Sader Method for the Determination of the Spring Constant of a Cantilever	170
12.5.4	Thermal Method for the Determination of the Spring Constant of a Cantilever	170
12.5.5	Experimental Determination of the Sensitivity and Spring Constant in AFM Without Tip-Sample Contact	174
12.6	Summary	175
13	Static Atomic Force Microscopy	177
13.1	Principles of Static Atomic Force Microscopy	177
13.2	Properties of Static AFM Imaging	179
13.3	Constant Height Mode in Static AFM	180
13.4	Friction Force Microscopy (FFM)	181
13.5	Force-Distance Curves	182
13.6	Summary	186
14	Amplitude Modulation (AM) Mode in Dynamic Atomic Force Microscopy	187
14.1	Parameters of Dynamic Atomic Force Microscopy	187
14.2	Principles of Dynamic Atomic Force Microscopy I (Amplitude Modulation).	188
14.3	Amplitude Modulation (AM) Detection Scheme in Dynamic Atomic Force Microscopy	193
14.4	Experimental Realization of the AM Detection Mode	196
14.5	Time Constant in AM Detection	198
14.6	Dissipative Interactions in Non-contact AFM in the Small Amplitude Limit	200
14.7	Dependence of the Phase on the Damping and on the Force Gradient	203
14.8	Summary	204

15	Intermittent Contact Mode/Tapping Mode	205
15.1	Atomic Force Microscopy with Large Oscillation Amplitudes	205
15.2	Resonance Curve for an Anharmonic Force-Distance Dependence	211
15.3	Amplitude Instabilities for an Anharmonic Oscillator	213
15.4	Energy Dissipation in Dynamic Atomic Force Microscopy	217
15.5	Properties of the Intermittent Contact Mode/Tapping Mode	220
15.6	Summary	221
16	Mapping of Mechanical Properties Using Force-Distance Curves	223
16.1	Principles of Force-Distance Curve Mapping	223
16.2	Mapping of the Mechanical Properties of the Sample	226
16.3	Summary	227
17	Frequency Modulation (FM) Mode in Dynamic Atomic Force Microscopy—Non-contact Atomic Force Microscopy	229
17.1	Principles of Dynamic Atomic Force Microscopy II	229
17.1.1	Expression for the Frequency Shift	232
17.1.2	Normalized Frequency Shift in the Large Amplitude Limit	235
17.1.3	Recovery of the Tip-Sample Force	238
17.2	Experimental Realization of the FM Detection Scheme	238
17.2.1	Self-excitation Mode	238
17.2.2	Frequency Detection with a Phase-Locked Loop (PLL)	244
17.2.3	PLL Tracking Mode	248
17.3	The Non-monotonous Frequency Shift in AFM	250
17.4	Comparison of Different AFM Modes	251
17.5	Summary	252
18	Noise in Atomic Force Microscopy	255
18.1	Thermal Noise Density of a Harmonic Oscillator	255
18.2	Thermal Noise in the Static AFM Mode	258
18.3	Thermal Noise in the Dynamic AFM Mode with AM Detection	258
18.4	Thermal Noise in Dynamic AFM with FM Detection	260
18.5	Sensor Displacement Noise in the FM Detection Mode	262
18.6	Total Noise in the FM Detection Mode	263
18.7	Comparison to Noise in STM	264
18.8	Signal-to-Noise Ratio in Atomic Force Microscopy FM Detection	265
18.9	Summary	267

19	Quartz Sensors in Atomic Force Microscopy	269
19.1	Tuning Fork Quartz Sensor	269
19.2	Quartz Needle Sensor	270
19.3	Determination of the Sensitivity of Quartz Sensors	273
19.4	Summary	275

Part III Scanning Tunneling Microscopy and Spectroscopy

20	Scanning Tunneling Microscopy	279
20.1	One-Dimensional Potential Barrier Model	279
20.2	Flux of Matter and Charge in Quantum Mechanics	284
20.3	The WKB Approximation for Tunneling	286
20.4	Density of States	288
20.5	Bardeen Model for Tunneling	289
20.5.1	Energy-Dependent Approximation of the Bardeen Model	292
20.5.2	Tersoff-Hamann Approximation of the Bardeen Model	300
20.6	Constant Current Mode and Constant Height Mode	302
20.7	Voltage-Dependent Imaging	304
20.8	Summary	306
21	Scanning Tunneling Spectroscopy (STS)	309
21.1	Scanning Tunneling Spectroscopy—Overview	309
21.2	Experimental Realization of Spectroscopy with STM	310
21.3	Normalized Differential Conductance	313
21.4	Relation Between Differential Conductance and the Density of States	316
21.5	Recovery of the Density of States	319
21.6	Asymmetry in the Tunneling Spectra	322
21.7	Beyond the 1D Barrier Approximation	324
21.8	Energy Resolution in Scanning Tunneling Spectroscopy	324
21.9	Barrier Height Spectroscopy	327
21.10	Barrier Resonances	329
21.11	Spectroscopic Imaging	330
21.11.1	Example: Spectroscopy of the Si(7×7) Surface	330
21.12	Summary	333

22	Vibrational Spectroscopy with the STM	335
22.1	Principles of Inelastic Tunneling Spectroscopy with the STM	335
22.2	Examples of Vibrational Spectra Obtained with the STM . . .	337
22.3	Summary	340
23	Spectroscopy and Imaging of Surface States	341
23.1	Energy Dependence of the Density of States in Two, One and Zero Dimensions	341
23.2	Scattering of Surface State Electrons at Surface Defects	345
23.3	Summary	347
24	Building Nanostructures Atom by Atom	349
24.1	Positioning of Single Atoms and Molecules by STM	349
24.2	Electron Confinement in Nanoscale Cages	354
24.3	Inducing a Single Molecule Chemical Reaction with the STM Tip	356
24.4	Summary	357
	Appendix A: Horizontal Piezo Constant for a Tube Piezo Element . . .	359
	Appendix B: Fermi's Golden Rule and Bardeen's Matrix Elements . . .	363
	Appendix C: Frequency Noise in FM Detection	371
	References	375
	Index	377